A Tribute to Jim Williams

Electronics (1974-1981)

Dc differential voltmeter resolves 1 microvolt

by James Williams
Massachusetts Institute of Technology, Cambridge, Mass.

If you're dissatisfied with the choice of commercially available dc differential voltmeters, here's a high-performance unit that you can build yourself for about $800. Besides functioning as a high-resolution differential voltmeter, this instrument can serve as a picoammeter or an an adjustable voltage-reference source. It affords good stability, an absolute five-place accuracy of ±0.001%, and a resolution of 1 microvolt. It also provides an output for a ground-referenced stripchart recorder and overload protection for its nullmeter.

The voltmeter is intended for use with standard cells, temperature-compensated zener diodes, and other precision low-voltage sources. Its input voltage range is 0 to 10 V, and its operating temperature range is 20°C to 30°C.

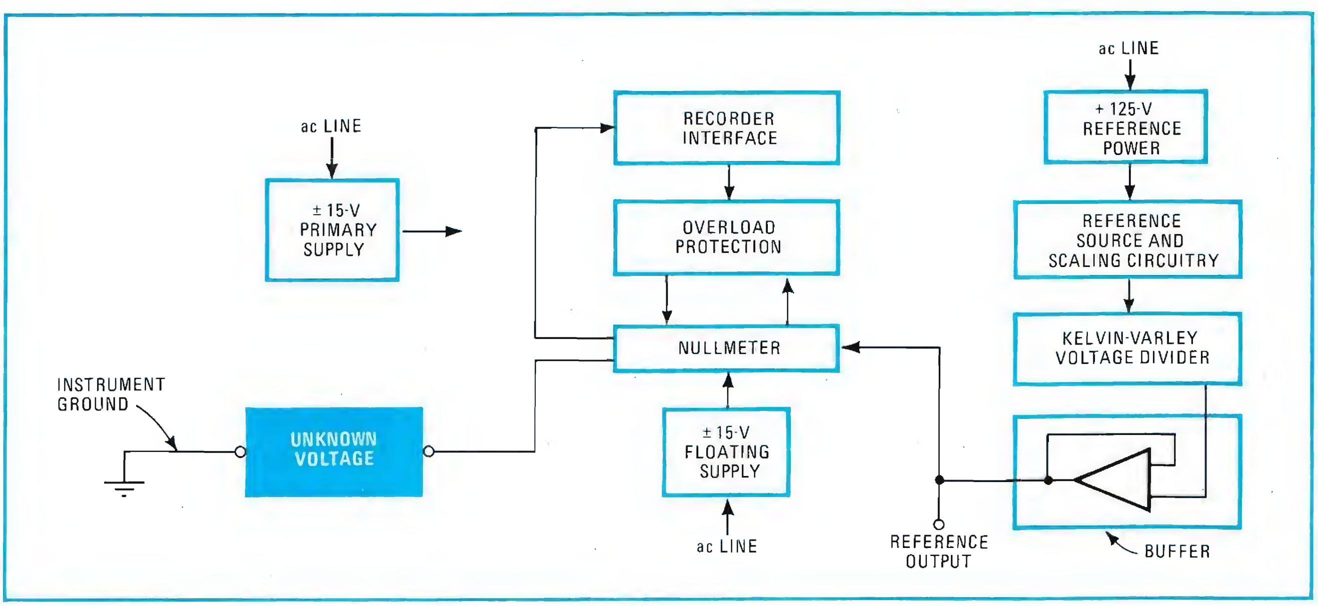
In general, a high-resolution differential voltmeter makes a measurement in a classical potentiometric way. A stable voltage reference is placed across a variable voltage divider, whose output is applied to one input of a high-sensitivity voltmeter. The voltage to be measured is applied to the other input of the voltmeter. When the divider is adjusted to the same potential as the unknown voltage, the voltmeter will read zero. Since no current flows through the voltmeter during null, the unknown voltage sees an infinite impedance.

The block diagram of the voltmeter is given in Fig. 1. The instrument includes a high-stability solid-state voltage-reference source and a nullmeter having a full-scale resolution as fine as 5 μV. Since the input impedance of the nullmeter is known, the unit can also function as a highly accurate picoammeter for determining low-level offset and bias currents. If the meter goes off scale, there are indicators to show which way to bring the meter back on scale.

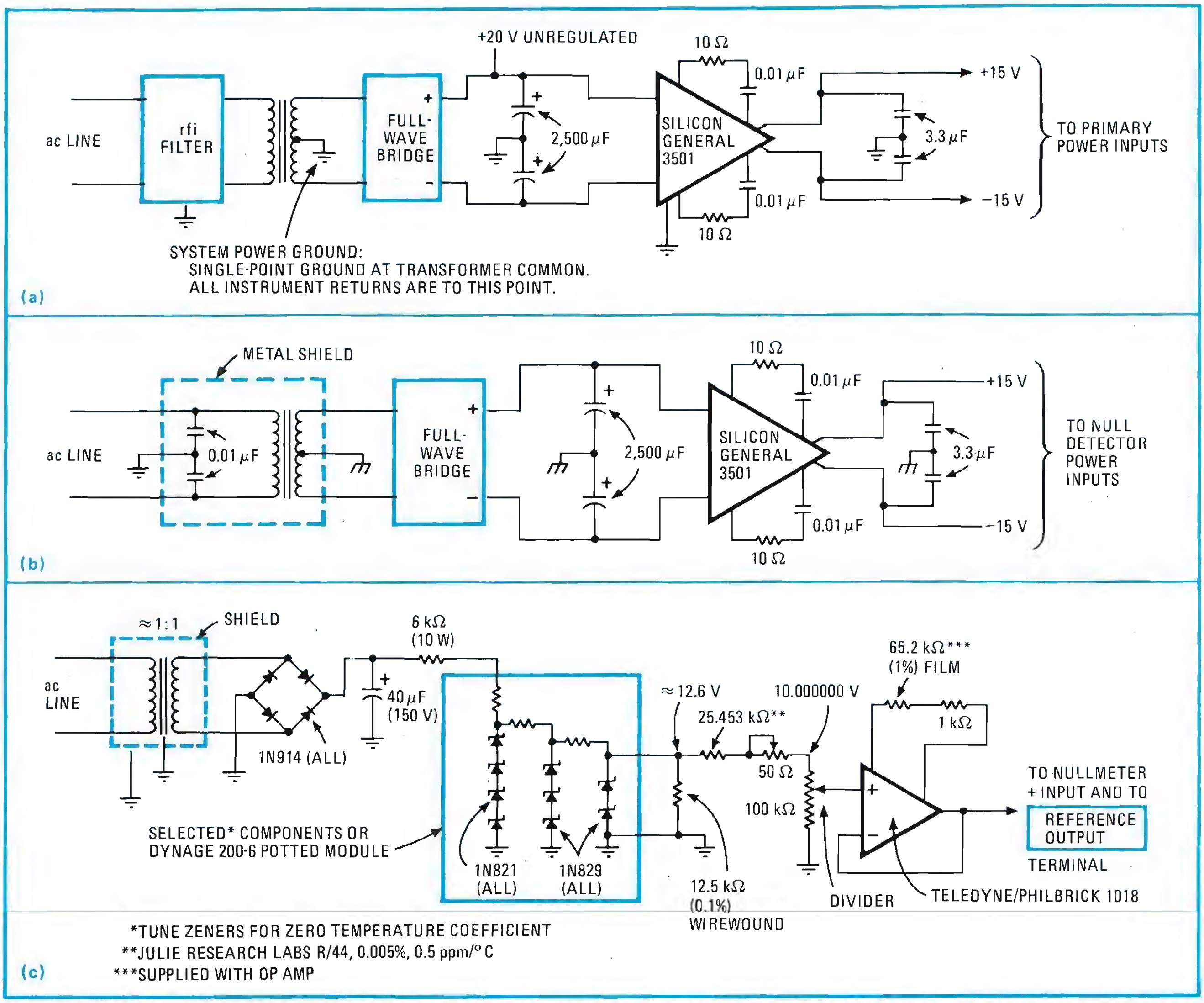
The output for the ground-referenced stripchart recorder is derived from the floating nullmeter without introducing leakage across either the voltage divider or the voltage to be measured. The buffer amplifier connected to the divider permits the voltmeter to be used as a variable voltage-reference source that can be set to within ±0.001%.

Briefly, here's how the instrument works. The ac line furnishes power to both the 125-V unregulated supply and the two ±15-V supplies, one of which is floating. The 125-V supply acts as a pseudo-current source while driving the voltage-reference source. The output of the reference, which is approximately 12.6 V, is resistively scaled to 10.000000 V (at 25°C) across the Kelvin-Varley voltage divider. The divider's output is buffered by an ultra-stable unity-gain amplifier that provides the REFERENCE OUTPUT terminal for the instrument. When the output from the divider equals the unknown voltage, the nullmeter will read zero so that the unknown is then equal to the divider setting.

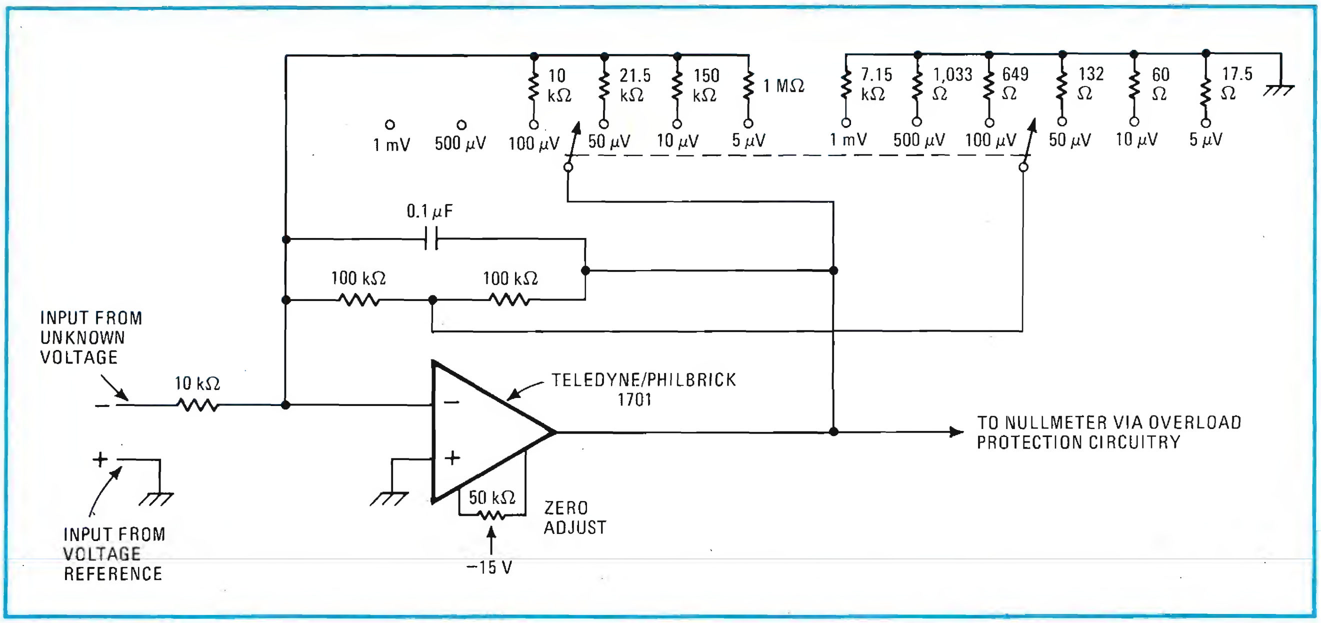
For the ±15-V primary power supply (Fig. 2a), a monolithic tracking voltage regulator is wired in its standard configuration. The two 10-ohm resistors provide overload sensing, and the capacitors smooth out and prevent spurious oscillations. System ground is at



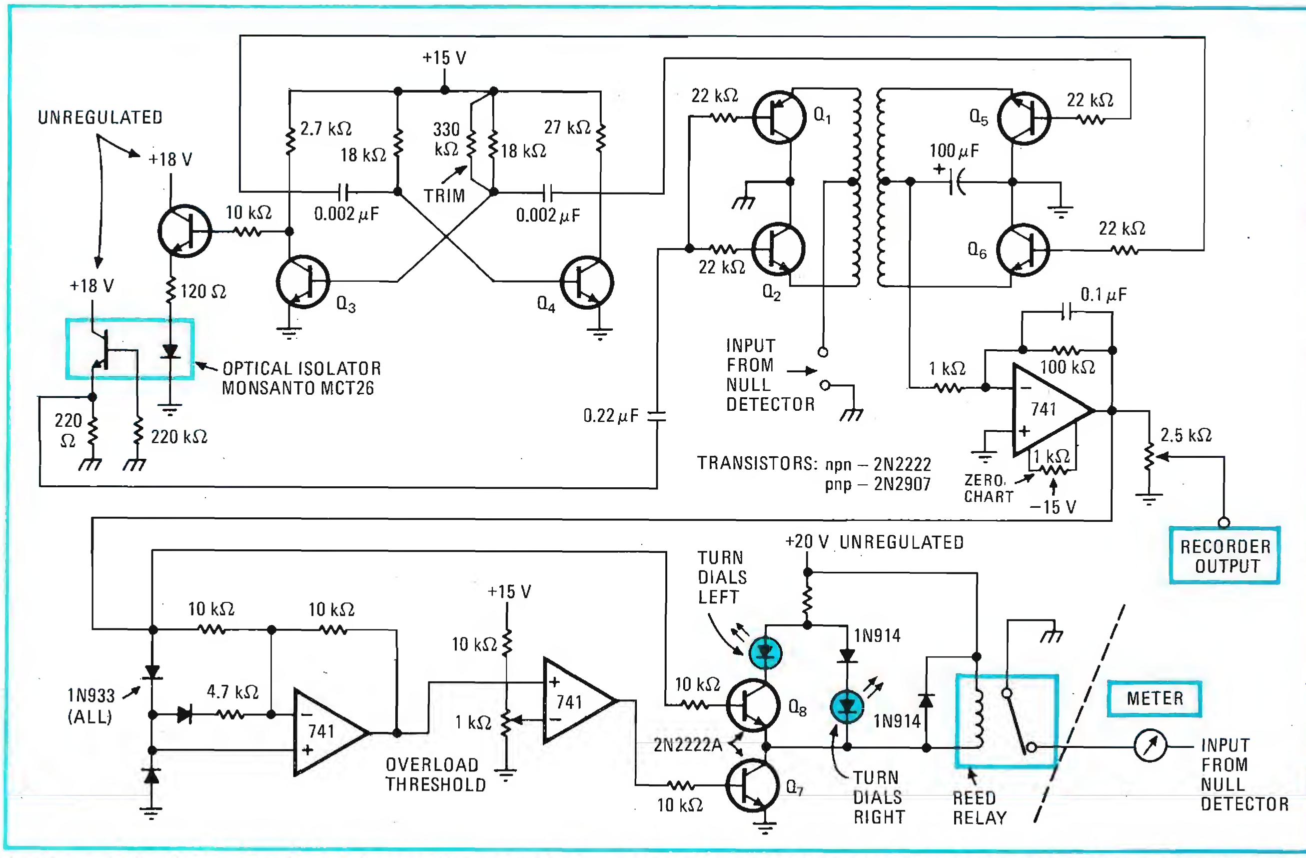
1. Performance plus trimmings. This high-resolution differential voltmeter takes advantage of modern solid-state technology to provide both accuracy and stability at reasonable cost. Its floating nullmeter, which is protected against overloads, assures a true differential measurement. The instrument also has a settable voltage-reference output, as well as a ground-referenced output for a stripchart recorder.



2. The voltage sources. The voltmeter's primary ±15-V supply (a) is ground-referenced, but the ±15-V supply (b) for its null detector is floating. The ultra-stable reference source (c), which is used to match the unknown voltage, contains an array of specially selected zeners.



3. Precision null detector. A chopper-stabilized amplifier is at the heart of the instrument's null detector. A T-type feedback network, which is used to set amplifier gain, minimizes leakage problems and keeps the sizes of the feedback resistances at practical levels.



4. The outputs. A ground-referenced output for a stripchart recorder is developed from the null-detector's output by isolating the floating detector with an optical coupler. LED indicators show which way to null the meter. The reed relay disconnects the meter during overloads.

the transformer common, and all common power returns are brought to this point. There are no common power bus lines in the instrument—a precaution that must be taken to avoid corrupted grounds. Moreover, an rfi filter is used to block spikes from the ac line. A similar circuit, (Fig. 2b), but one with a floating ground, is used for supplying the instrument's null detector.

The voltage-reference source (Fig. 2c) is powered by the voltage derived from the transformer and its rectification components. The cascaded temperature-compensated zener diodes are specially selected for optimum matched parameters and are aged to produce stabilities greater than those of unsaturated standard cells. But a commercially available module can be used instead, if desired.

The reference output is scaled to 10 V across the divider. An ultra-stable, low-bias-current op amp buffers the output of the divider for the instrument's nullmeter input and its REFERENCE OUTPUT terminal. The output current for the voltage reference can range from 0 to 3.5 milliamperes. Its stability is ±1 ppm for a 10% shift in line voltage, ±2 ppm for a 1°C change in operating temperature, and ±5 μV maximum over a 24-hour period.

The instrument's null detector (Fig. 3) is designed around a chopper-stabilized amplifier. Since it is powered by a floating supply, this amplifier sees a true differential signal at its inputs. The power common line is used as one of the inputs, but the power and signal common returns are separated to minimize grounding loops and noise. A T-type feedback network sets amplifier gain, helps to hold feedback resistances to practical levels, and avoids leakage problems.

Overload protection for the meter movement and the output for a stripchart recorder are provided by the circuit of Fig. 4. The ground-referenced recorder output preserves the integrity of the nullmeter's true floating ground and simplifies the interfacing of the recording device.

The input for this circuit, which is the output from the null detector, drives the pulse-amplitude modulator formed by the transformer and transistors Q_1 and Q_2. The signal is chopped at the frequency set by the multivibrator made up of transistors Q_3 and Q_4. The chopping drive signal must be fed through an optical isolator because the multivibrator, which is the source of the chopping signal, is instrument-grounded. The signal that appears at the transformer secondary is demodulated synchronously by transistors Q_5 and Q_6. The multivibrator's trim resistor is selected to give a symmetrical swing about zero at the demodulated output. This output is then amplified for the recorder hookup.

The input for the overload protection circuit is taken from the signal developed for the stripchart recorder. The first stage of this circuit takes the absolute value of the recorder output. When the meter is overloaded, transistor Q_7 conducts. If the base voltage of transistor Q_8 is high, the meter is off scale in its plus zone, and the TURN DIALS LEFT indicator will light. If Q_8's base is low, the meter is off scale in its minus zone, and the TURN DIALS RIGHT indicator will come on. In either case, the reed relay disconnects the meter during an overload. □

Comparator IC forms 10-bit a-d converter

by James M. Williams
Massachusetts Institute of Technology, Cambridge, Mass.

This analog-to-digital converter uses an integrated-circuit comparator to provide an accurate 10-bit representation of an analog signal in 1 millisecond or in 100 microseconds, depending on the clock rate. The circuit, which costs only $13 to build, is accurate over the temperature range from 15°C to 35°C.

In addition to low cost, advantages include low parts count, low power drain, immunity from power-supply fluctuations, and capability to transmit data over two wires. Disadvantages include the necessity for a stable clock (although one clock can serve many converters), and dependence upon a capacitor for stability. The circuit may be sensitive to noise, but a small RC filter can be used for noise suppression.

Operation over extended temperature ranges is not recommended. If such use is necessary, however, capacitor C (Fig. 1) should consist of a 0.03 silver-mica capacitor in parallel with a 0.01 polystyrene capacitor.

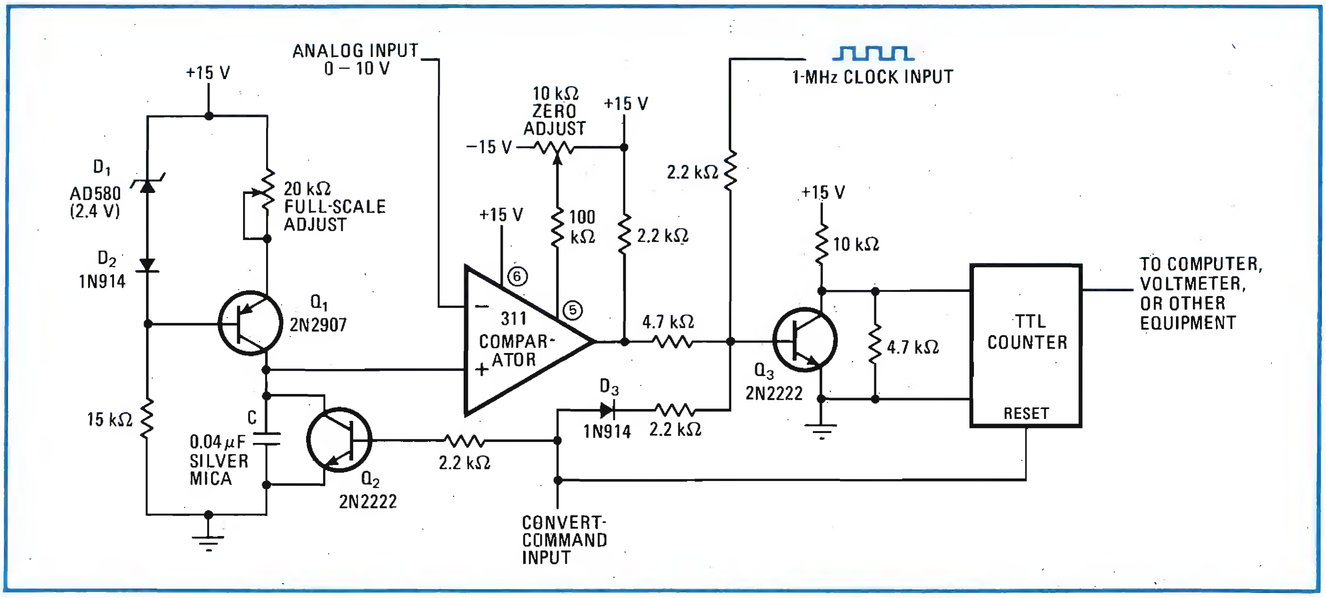
The digital output from this converter is the number of clock pulses counted during the time required for the capacitor to charge up to the level of the analog voltage. As the circuit diagram in Fig. 1 shows, the analog input can be any voltage from 0 to 10 V. This voltage and the voltage across the capacitor are compared in the IC. As long as the analog voltage is greater than capacitor voltage V_C, the comparator allows a counter to count clock pulses. But when V_C reaches the level of the analog voltage, the counting is stopped. The total number of pulses counted is a measure of the analog input. The charging rate of the capacitor is set so the pulse count is proportional to the voltage; e.g., 1,000 pulses corresponds to 10 V.

The detailed operation of the a-d converter in Fig. 1 is straightforward. Transistor Q_1, diodes D_1 and D_2, and the resistors constitute a constant-current source for charging capacitor C. The 2.4-V zener D_1 stabilizes the source against power-supply variations, and the voltage drop across D_2 matches the emitter-to-base voltage in Q_1, despite any temperature changes.

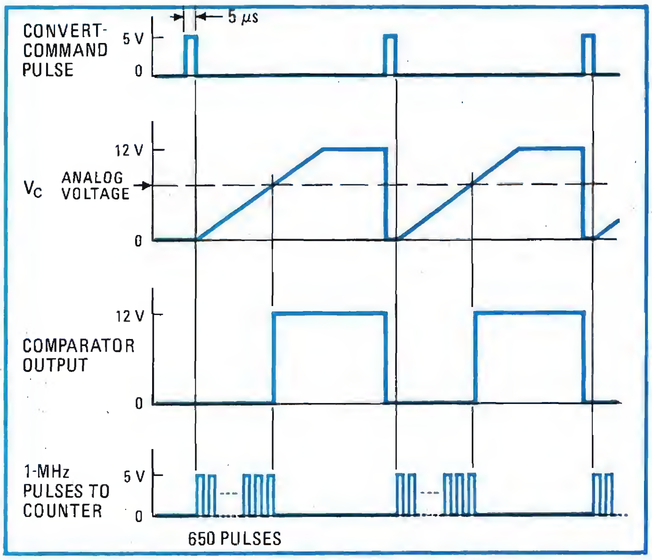
The type 311 IC compares the input voltage to the capacitor voltage V_C and controls transistor Q_3. The input voltage is applied to the inverting (−) input of the comparator, and V_C is applied to the noninverting (+) terminal. At quiescence, V_C is about 12 V, so the 311 output is high. This high signal keeps Q_3 on, so that the data line into the counter is grounded and no clock pulses are counted.

When a convert-command pulse is applied, transistor Q_2 turns on and discharges C, so that the 311 output goes to zero. Diode D_3 and the 2.2-kilohm resistor keep Q_3 on, however, so that no pulses can be counted during the convert command. On the falling edge of the command pulse, Q_1 begins to charge C linearly, and D_3 ceases to hold Q_3 on.

Now, because the output of the comparator is low, the clock pulses can turn Q_3 on and off, so that clock-frequency pulses are delivered to the counter. The combination of the 10-kilohm resistor and the 4.7-kilohm resistor makes the level of these pulses compatible with



1. A-d converter. Integrated-circuit comparator permits counting of clock pulses only while capacitor is charging up to level of analog voltage. With 1-MHz clock shown, conversion of 10-volt analog voltage to 10 bits (1,000 counts) takes 1 millisecond. If clock rate is 10 MHz, and C is 0.004 µF, conversion is accomplished in 100 microseconds.



2. Timing diagram. For an analog voltage of 6.5 V as in this example, 650 pulses are counted while capacitor charges up to turn off comparator output. Convert commands can be given at any rate up to 1 kHz for circuit as shown in Fig. 1.

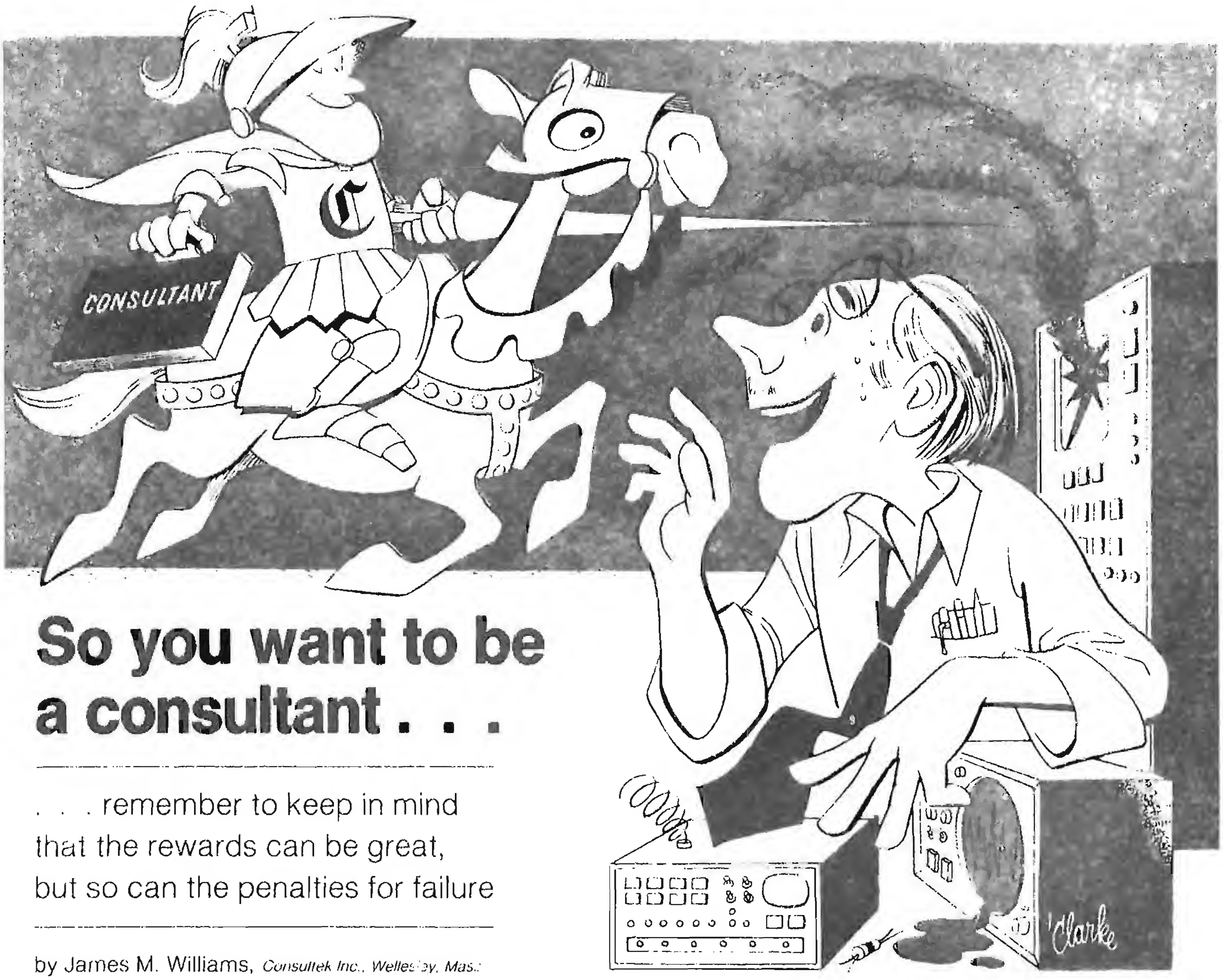
transistor-transistor logic (TTL) in the counter circuit.

When V_C charges up to the level of the input voltage, the 311 output goes high again, which turns on Q_3 and grounds the data line so that no more pulses are counted. Fig. 2 shows the timing diagram for the converter operation.

To calibrate the counter, a 10-V signal is applied at the input, and the 20-kilohm potentiometer is adjusted so that 1,000 pulses appear at the counter for each conversion command. Then a 0.01-V signal is applied, and the 10-kilohm pot is adjusted so that 1 pulse is counted for each conversion. The unorthodox voltage-offset adjustment for the comparator corrects for incomplete discharge of C; the minimum voltage across C is V_{CE}(sat) of Q_2.

The circuit in Fig. 1 can convert 10 bits (i.e., count 1,000 pulses) in 1 ms. For conversion in 100 μs, the clock frequency must be 10 megahertz, and C must be 0.004 microfarad. Conversion commands can then be given at rates up to 10 kilohertz. □

Designer's casebook is a regular feature in Electronics. We invite readers to submit original and unpublished circuit ideas and solutions to design problems. Explain briefly but thoroughly the circuit's operating principle and purpose. We'll pay $50 for each item published.



So you want to be a consultant . . .

. . . remember to keep in mind that the rewards can be great, but so can the penalties for failure

by James M. Williams, *Consultek Inc., Wellesley, Mass.*

☐ When the company parking lot begins to look gray and familiar, many electronics engineers start dreaming about challenge and diversity. They often come to feel that a good way to achieve independence is consulting—a way of life that also draws EEs who make the move at the outset of their careers, as well as those who are between jobs or have time to moonlight.

But deciding to be a consulting engineer is a lot easier than becoming one. Most prospective consultants are not aware of the range of potential jobs, much less how to get them. Nor are they familiar with the business side, especially fees and contracts, or with the special problems a consultant faces on the job.

Necessary traits

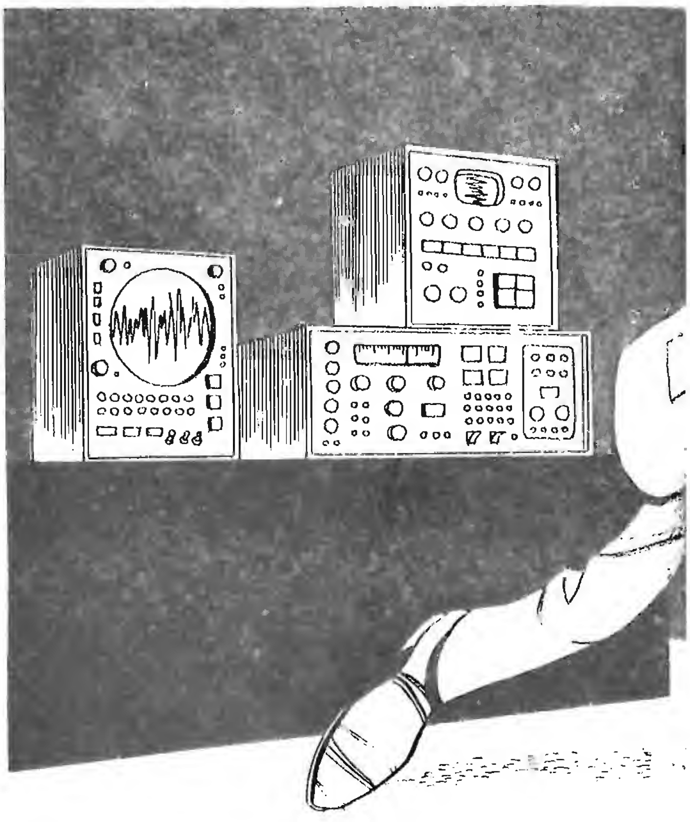
Engineering consulting can be challenging, profitable, and just plain fun. But it can also be a nightmarish conflict between the consultant and his clients involving lost time, overestimation of abilities, poor decisions, and worse. A sobering fact is the failure of the majority of engineers calling themselves consultants to establish a going business. Most of them should not have gone into consulting in the first place.

What separates the winners from the losers? Successful consultants all seem to have the ability to listen, the facility to think fast and clearly under pressure, self-confidence based on technical expertise and experience, a high level of motivation and interest in engineering, and salesmanship. Of course, these traits apply to almost any successful engineer, so you might say that a successful consulting engineer is first and foremost a fine engineer with a little something extra.

The vision of consultants as mental giants who should be able to do anything is wrong. In many situations, the consultant is part of a team effort; very often he and his client will augment each other's know-how. Therefore it is wise for a client to know from the beginning what the consultant can and cannot do.

A smart consultant does not promise the moon in an eager attempt to land a contract. Trying to con a client

One danger is getting caught between conflicting personalities in a company



into believing that you can do something you cannot deliver is simply asking for a damaged reputation, a lawsuit, or both.

The projects open to the consulting engineer vary widely. Usually a firm hires a consultant to provide a specialty it lacks or backup in technologies in which it is weak. I once worked for an optical-equipment manufacturer needing an oven that would cool down at a precise rate over several thousand hours. The firm could not buy it and did not know how to make it.

What consultants do

Many companies rely on outside help to get them started in a new product line while they develop in-house expertise. A good example is a project I did for a digital-equipment manufacturer. The firm wanted to come out with a line of low-level analog modules to plug into its existing digital systems. My duties included both startup design for the modules and interviewing candidates for the company's newly formed analog design team.

Electronics manufacturers often farm out specific tasks as well. For instance, I developed a production instrument for a maker of a certain type of environmental sensor. The sensor design itself was fine, but management wanted to add to the sales catalog an instrument designed around it. The firm was not willing to invest in a full-time engineer for a single new product.

Rescue operations are another form of consulting work. I once got a call from a firm where the senior engineer had died suddenly. He had been working on a new instrument, but had left almost no documentation, no specifications, no trimming procedures, no production tolerances, and no complete schematics.

It was a tight situation; time was short and cash flow limited, so the company needed a crash rescue operation. To finish the job, I sat down at the bench with what notes there were and the prototypes. From these I put together production schematics and created the other documentation required to get into production.

Another rescue involved a case where thousands of high-quality printed boards had been made up in advance for a circuit that did not work. These multilayer boards were tightly laid out, perfectly etched, precision-drilled, and very expensive. The problem was to get the circuit to work perfectly without altering the boards. In addition, there were restrictions on weight, power consumption, component size, and operating temperatures. And there could be no fudging on performance.

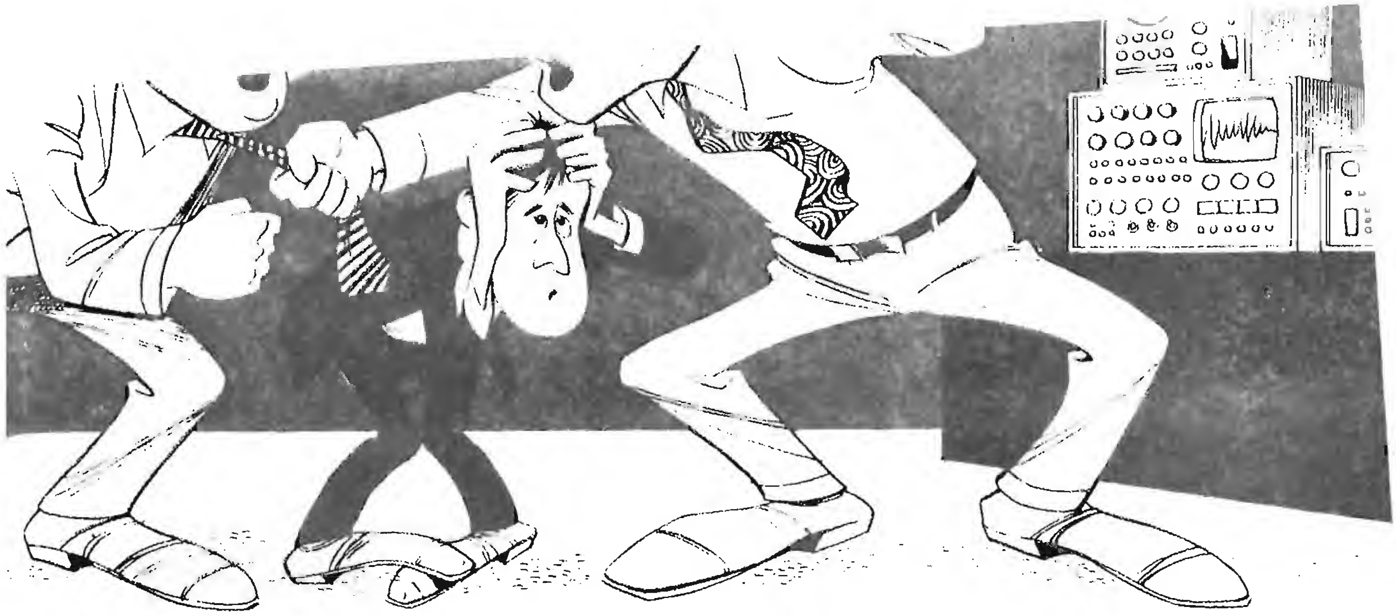
It was one of the most difficult assignments a consultant could get. The solution came down to analyzing the combination of functions and patterns that would perform to spec and conform to the board. It meant changing some components and changing values on others, a maddening procedure given the limits imposed.

Teaching is a possibility

Another possibility for a consultant is teaching special courses. Many companies prefer bringing the teacher to the students, rather than sending engineers to extension courses or night school. The advantages include lower cost, less time lost, and control over course content.

I have taught in-house courses in which the content was tailored to technologies the company was entering. One three-week course was a concentrated study of low-level analog circuits. Circuit performance and quality were the main concerns, with cost a secondary consideration. Another firm wanted its engineers to learn how to cut costs. So I taught a course on design shortcuts, such as one- and two-chip solutions to problems that appeared to require half a dozen integrated circuits.

Two other areas in which consultants sometimes work are technical writing and equipment-purchase recommendations. Data sheets, application notes, manuals, and even magazine articles are often farmed out in order to meet deadlines for the introduction of new products. As for purchasing recommendations, some firms hire a



consultant because their personnel have little background in electronics. Such a customer wants to make sure that it is spending money wisely in choosing test instruments and the like.

Along this line, I have also been asked to analyze competitive products. A circuit house, for instance, wanted to evaluate its high-grade chopper-stabilized amplifier against that of a competitor. The objective was to decide whether to expand its line to include models with features similar to the competitive unit.

Another form of consulting is developing a product design or patent independently and then selling it outright to a company that will manufacture it. The design effort can include anything from a black-box function to a complete instrument.

Finding work takes persistence

So much for the types of work available to the consultant. The next problem is how to land a job.

The key to getting work is mastering the art of thoughtful aggression—that is, spotting a potential opening and going after it. It means reading engineering periodicals to keep up to date on who is doing what. Is XYZ Inc. going into a new business? Do prices at ABC Corp. seem too high? Do product trends indicate an established firm is falling behind more progressive newcomers? Any one of these companies may be in the market for help from a consultant.

Besides the engineering magazines, general business publications can also provide leads. Say Acme Shoe Co. reports it is planning to spend a few million dollars on automating production—an inquiry is in order. Or suppose Ajax Cardboard Corp. decides to diversify into data-processing products—business may be waiting.

Look at products you use yourself Do they work well? Could you do a better design job? What about companion products, additional features, and the like? Are the data sheets or technical manuals clearly written and well illustrated? My first consulting project involved a premium product of top performance that I had been using. The data sheet was dull and poorly written, and the applications in it did not do justice to the product. I called and got the job of rewriting the data sheet.

Exposure on conference or symposium programs and in magazine articles is important too. The more work a consultant does, the more often other opportunities come his way by word of mouth.

Generally, though, the consultant has to approach the potential client—and this inquiry has to be well planned. A letter is one way to start, but a telephone call to the president or other high officer in the company is often better. It is always best to go to the top of a company first. Once you interest a key executive, the doors will open, whereas middle-echelon personnel may either feel threatened by a consultant or simply not have the authority to start the ball rolling.

The letter or telephone call should get straight to the point. The consultant describes who he is and how he thinks he can be of service in as specific terms as possible. Suggestions for a new product or a product upgrading should also be straightforward in order to provide the executive with enough information for evaluation without overwhelming him with details.

Very few consulting contracts are arranged without a meeting. Often a serious prospective client will offer to pay travel expenses for a preliminary get-together. However, once a contract is drawn up, travel expenses should be explicitly provided for or else lumped together with the total charge for the job.

When a company shows real interest, respond quickly. If you started with a telephone call, then a letter should follow, restating the conversation. If a letter spawned interest, then perhaps a telephone call is in order. The idea is to get negotiations moving quickly without becoming pushy. Sometimes a company simply cannot reply immediately because of size or internal communi-

For the established consultant, annual income can run from $30,000 all the way up to $75,000

cations difficulties. In any case, the consultant has to be ready to talk when the prospect is ready.

The period between initial approach and contract meeting is a good time for the consultant to get his case together. When the call comes, he will be ready with a plan and a fee to begin negotiations. After holding initial meetings, the consultant usually will write proposals, which are evaluated, discussed, and often revised.

Inventions: a special case

Finding a company to market an invention is probably harder than dreaming up the product. Knowing what design idea is saleable, to whom, when, and for what price are complex matters. And the lone engineering consultant trying to sell an idea is in a vulnerable position. Negotiations often resemble a poker game.

Some guidelines might be helpful, however. First, decide what the product is worth and do not sell for less. Of course, this decision involves considerable background research. You must estimate production costs, overhead, profit margin, marketability, and product life—all factors that the company probably knows quite well.

Negotiations over selling a product can go on for an incredibly long time and can appear fruitless. However, drawing out the discussions is often a tactic on the part of the company to shake the product loose from the disheartened inventor. So it is wise not to give into low bids or delaying tactics if you are confident that your product is a winner and if you have done your cost-analysis homework. Needless to say, competent legal advice should be sought before signing anything.

The business side of consulting is extremely important, yet it is surprising how sloppy many consultants are in this area. Only after listening to a prospective client's problem and making sure that it is understood, can a consultant come to a meaningful figure for the fee.

It is wise to enter a situation with a ballpark figure in mind, but the nature of the project may have changed since your initial approach, or else the project may not have been adequately communicated in the first place. It is important to look out for these stumbling blocks before discussing the fee.

In any case, the most common error of novice consultants is setting the fee too low. Two hundred dollars a day and up is a common figure these days. The main thing is to be paid a fair amount. Occasionally companies will offer a royalty arrangement in place of direct payment or some combination of the two.

Every so often a company is in a great hurry to get something done and is willing to pay anything, no questions asked. I once got a call from a California outfit. The president explained that his staff had underestimated the problems in building an oven to maintain a stable temperature of 65°C to within 25 microdegrees.

Speed means money

The company, a subcontractor, had built a large system, left the oven until last, and had a site inspection scheduled in four days. Afraid of losing all or part of the subcontract, the company offered a flat $5,000 fee to get a control system up and running. With a number of technicians and machinists helping, the control loop was running after 40 hours of nonstop work.

Whatever the fee agreement, it is important to draw up a contract. Some consultants are afraid of insulting a potential customer by insisting on a contract, but this fear is unfounded. A contract provides a record of the agreement to avoid any misunderstandings and to protect both parties. Managers understand this.

Some contracts call for all the work to be completed before payment is made. Others provide for partial payments as certain contractually defined phases of a project are completed. Still others provide a retainer payment before any work begins. Usually the client prepares the contract and sends it to the consultant, who edits it and returns it. A contract may go back and forth two or three times before both are ready to sign.

Most contracts are relatively simple and pose no problem. On very rare occasions, the consultant runs into a client who is dishonest and refuses to pay. If this happens, it is best to try to remind him, or to reach an understanding-- but be firm. If the client does not respond, it may be necessary to retain a lawyer. However, a consultant should never threaten legal action as a bluff, since the client may call him on it.

Doing the job

Once a contract has been drawn up, work finally begins. At this point, the employer should have a clear idea of what the consultant's approach is and how he will solve a particular problem.

Above all, the consultant has to be prepared to recognize and correct a situation if it is not working out as planned. There is often a great deal of pressure from clients to get a project done on time within budget. It is difficult to walk into an unfamiliar situation and take charge immediately, yet clients want quick solutions, not excuses and complaints.

A potentially sticky problem arises when a consultant becomes caught between conflicting personalities in a company. Company politics, power struggles, petty games, jealousy, obstinacy, and plain stupidity often lurk in corporations and can easily trip up an unsuspecting consultant.

In one project, I worked for a company in which the test equipment was poor and out of calibration, the work area was poorly lit, the laboratory was a mess, and the so-called engineering staff did nothing but cash their paychecks. I did my work, made sure the firm was satisfied, and got out, glad to be free of the place.

However, if a consultant gets caught on a dead-end street, the best policy is to speak out plainly but tactfully. Discuss the problems with the managers involved o define who is in charge of what, who is responsible for the project, and where you fit into the picture.

Even though the circumstances may not be ideal, the main objective is to get the job done without blowing up or entering into pointless power struggles. There are exceptions to this policy. One group I worked with turned out to be willing to put products out the door that just were not ready to go. I did not want my reputation ruined by these bad products, so I resigned and told the company why.

Most jobs can be completed with minimal difficulty if you act professionally, provide first-rate documentation, and meet all deadlines. It is a good idea to call the client back several weeks after the project is completed to make sure he is still satisfied. This is an excellent way to drum up follow-on business, as well.

It is vital that a consultant maintain confidentiality. Many companies do not want it known that they hire consultants, much less what for. Sometimes a firm is reluctant to hire someone who has worked for a direct competitor. Much more troublesome are companies who want to find out what a consultant's former clients are doing. In the long run, it is in your best interest to tell them nothing, because word of unethical practices will get out eventually.

It can be done

Starting a consulting practice from scratch is difficult, but not impossible. If you are working for a company and thinking of going into consulting, cash savings will make the transition a lot less bumpy. There are some engineers who left companies, worked hard, and put together a consulting business from literally nothing.

Whether consulting becomes a transitional phase or the end point in a career is up to the individual. I have found it rewarding, challenging, and educational. It provides variety, independence, and opportunity to the engineer who seeks these rewards in his career. □

The pros and cons of consulting

Consulting offers a number of advantages to the electrical engineer. But there are also a number of drawbacks to keep in mind.

On the plus side, consulting offers broad exposure to engineering. A consultant is called upon to solve a variety of problems and can usually choose assignments that interest him.

In addition, the consultant works with a wide variety of people in a range of companies. In a month he may see the inside of more companies than the average engineer sees in a lifetime.

The consultant's professional life is relatively autonomous. He can set his own hours; that is, he can work the hours needed to do a job, rather than following a daily routine. Successful consultants take home more income than full-time engineers, set their own vacation schedule, and usually travel more than do most steadily employed engineers. Fees range from $25 an hour for beginners to $50 – $75 an hour for established consultants, with the very best getting $100 an hour. Annual income can run from $30,000 up to $75,000.

The consultant's life is probably riskier than the average engineer's. He must first of all dig up his own jobs, for there is no paycheck waiting for him if he has a bad month. And he has to be much more skilled in business management, law, and contract negotiations.

Fringe benefits, pension plans, and the like must be self-provided. Equipment and literature must be purchased, often money risked to land a contract.

In addition, prospective clients can drag out decisions for weeks or months, keeping a consultant on pins and needles. To justify his higher fees, a consultant must study more, work harder, and produce superior solutions faster than other engineers.

Salaried engineers who feel career insecurity, appreciate their fringe benefits and pensions, and fear technological obsolescence will make unhappy consultants. After all, the consulting engineer has the same economic concerns as everyone else—only more leeway in determining his fate.

On-chip transistors extend audio amp's design flexibility

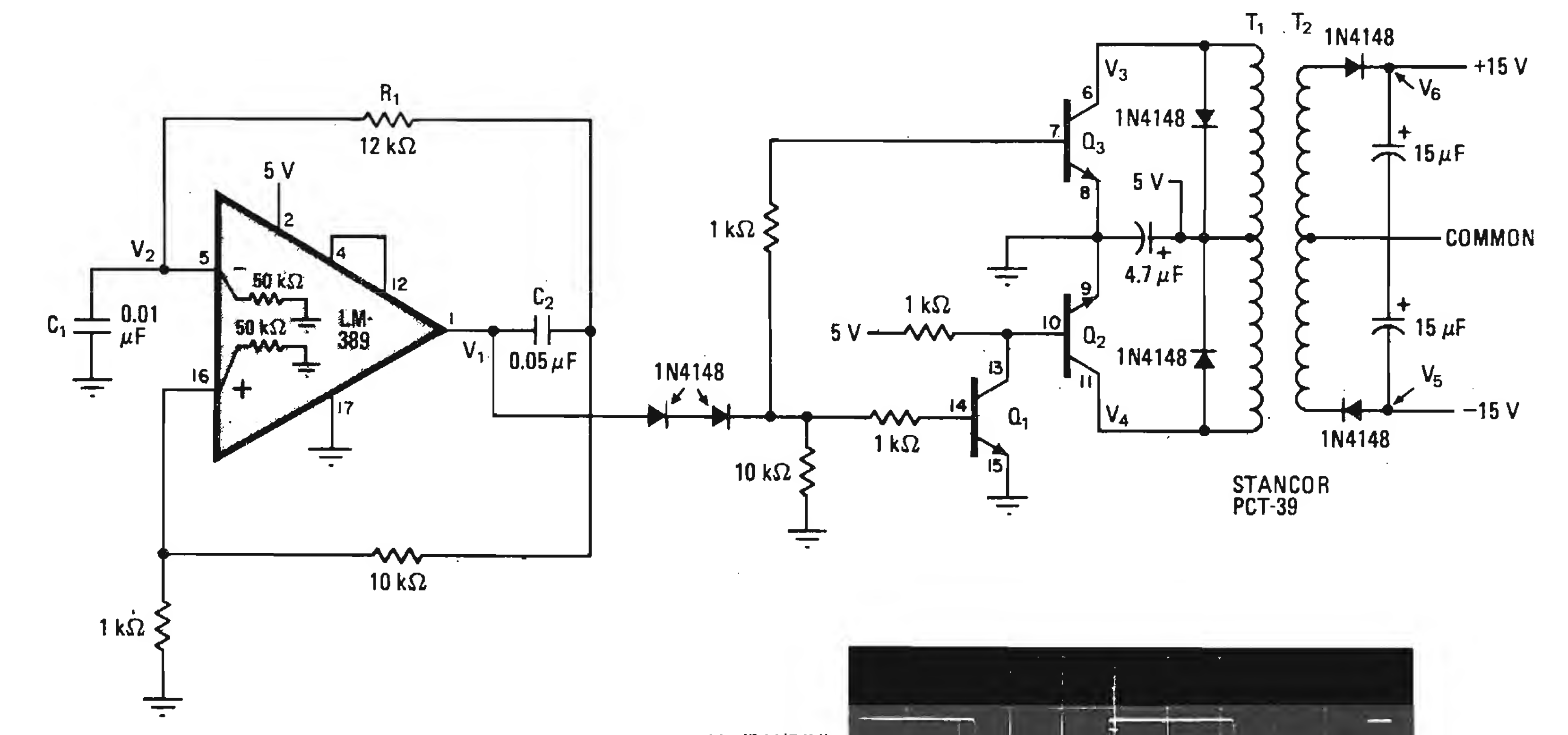
by Jim Williams
National Semiconductor Corp., Santa Clara, Calif.

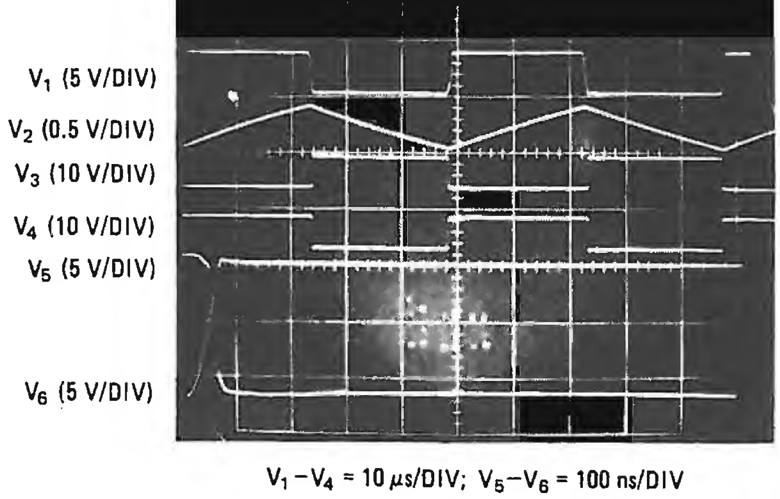
The availability of extremely low-cost audio-amplifier integrated circuits with on-chip transistor arrays, such as National's LM389, gives designers a great deal of flexibility in designing audio circuits. They make it much easier to develop low-cost versions of circuits unrelated to basic audio amplification, such as dc-dc converters, touch switches, stabilized frequency standards, scope calibrators, low-distortion oscillators, and logarithmic amplifiers. The designs of the often-needed converter, a bistable touch switch, and a tuning-fork frequency standard are discussed here in the first part of this two-part presentation.

The LM389 contains a 250-milliwatt audio amplifier and an array of three npn transistors, each of which is uncommitted. The amp has differential inputs and separate pins for setting its gain (from 20 to 200) via a resistor and runs off a single supply that may range from 4 to 15 volts. The three transistors have a minimum current-handling capability of 25 milliamperes and a minimum current gain of 100 for $V_{ce\,max}$ = 12 V and for a wide range of collector currents. The chip is therefore ideal for general use.

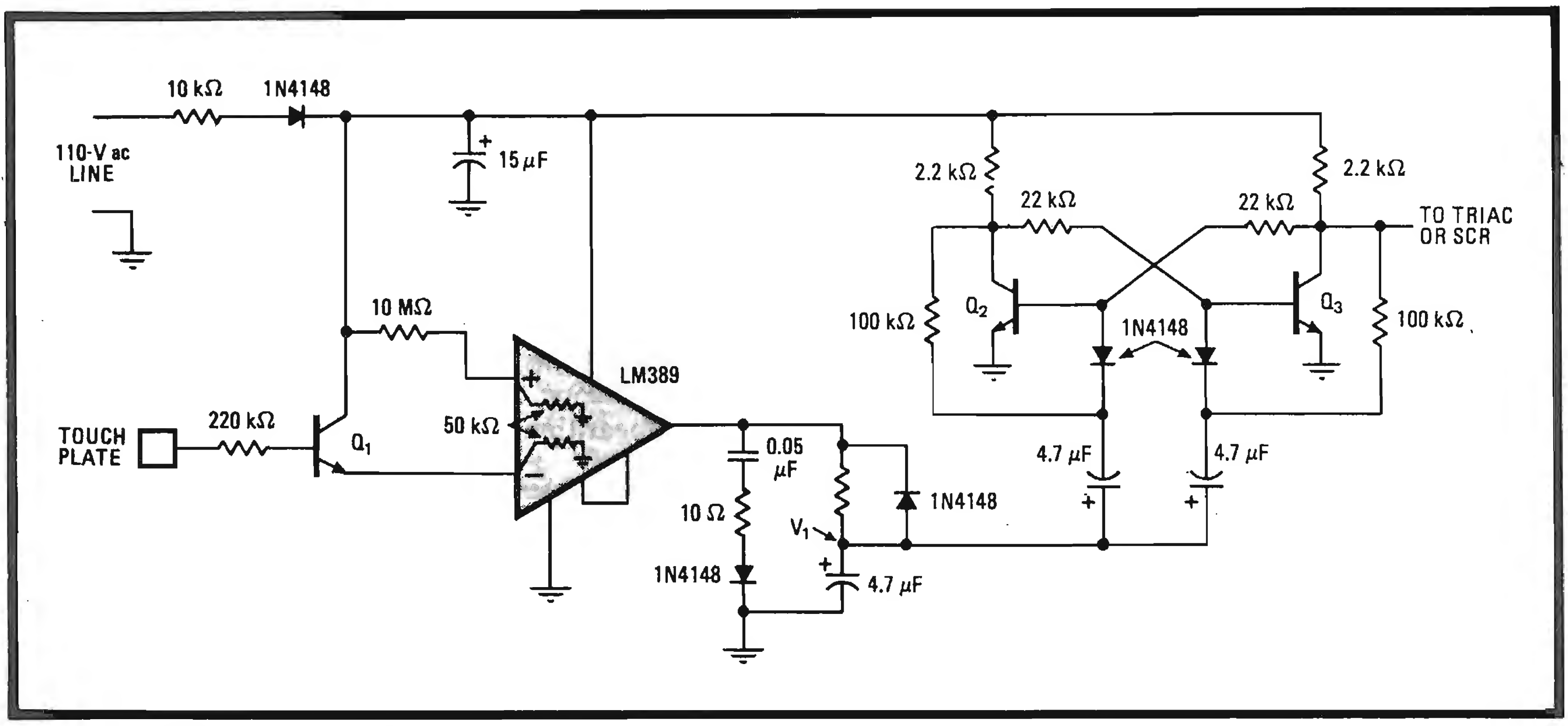
One area in which the chip will be useful is in dc-dc switching conversion. The device in Fig. 1 is intended for use as a power supply in a digital system where it is necessary to supply ±15 V to a low-power load. As can be seen from the oscilloscope photograph, the LM389 switches at 20 kilohertz. That rate is determined by the triangular-wave feedback signal, whose time constant is set by $R_1C_1C_2$, and its square-wave output is applied to transistors Q_1 and Q_3. The series diodes ensure clean turn-off for Q_1 and Q_3.

Q_1's inverted output drives one half of the transformer primary through Q_2, while Q_3 drives the other half. The diodes across Q_2 and Q_3 suppress spikes. Thus there is an

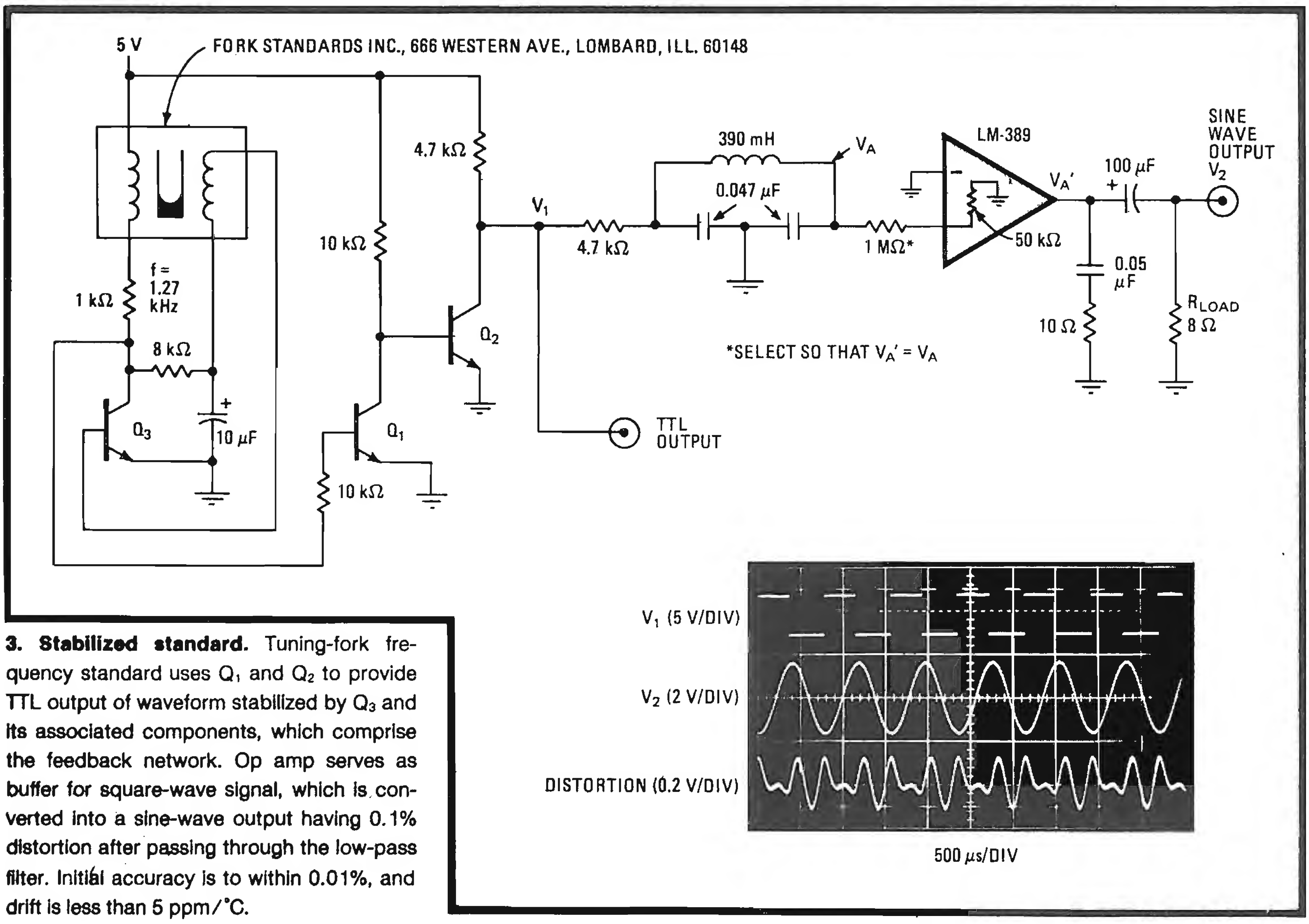




1. Condensed converter. Op amps with an on-chip transistor array, such as National's LM389, make inexpensive one-chip switching converters. Costing under \$10, unit shown provides ±1.5 mA at ±15 V for instrumentation amplifier. Scope photo displays waveforms at various points in circuit. Use of diodes in driver side of circuit allows spike suppression, plus clean switching.



2. Simple switching. Simple bistable touch switch may be similarly constructed. Op amp works as comparator and trigger for flip-flop Q_2–Q_3, which changes state each time plate is contacted. Thus, SCR at output may be alternately fired and switched off on command.



3. Stabilized standard. Tuning-fork frequency standard uses Q_1 and Q_2 to provide TTL output of waveform stabilized by Q_3 and its associated components, which comprise the feedback network. Op amp serves as buffer for square-wave signal, which is converted into a sine-wave output having 0.1% distortion after passing through the low-pass filter. Initial accuracy is to within 0.01%, and drift is less than 5 ppm/°C.

efficient step-up of voltage across T_2. This ac signal is rectified and filtered to produce complementary output voltages that may be used to power the desired linear components, in this case delivering ±1.5 mA, enough to power an operational or instrumentation amplifier.

The bistable touch switch (Fig. 2) allows a line-powered load to be controlled from a touch plate by means of a thyristor. Each time the plate is contacted, emitter-follower Q_1 conducts, permitting a fraction of the 60-hertz input signal to be applied to the inverting input of the amplifier. Consequently, the normally high output of the op amp follows the 60-Hz line input, causing V_1 to drop sharply.

This negative transition triggers a toggling flip-flop

formed by Q_2 and Q_3. In this manner, the output of the flip-flop changes state each time the touch plate is contacted, prompting the firing of the silicon controlled rectifier or triac that switches ac power to the load.

Figure 3 shows a tuning-fork frequency standard that is stabilized by appropriate feedback. Both sine-wave and TTL-compatible outputs are available. As the circuit needs only 5 V, it can run off a battery.

The tuning fork proper supplies a low-frequency output that is very stable (typically to within 5 ppm/°C) and has an initial accuracy of within 0.01%. Moreover, it will withstand vibration and shock that would fracture a quartz crystal. Here, Q_3 is set up in a feedback configuration that forces the fork to oscillate at its resonant frequency. Q_3's output is squared up by Q_1 and Q_2, which provide a TTL-compatible output. When passed through an LC filter and the op amp, which provides a low-impedance (8-ohm) output, the signal is converted into a sine wave having less than 1% distortion, as shown in the figure.

Several other useful circuits also can be built. The second part of this article will deal with the chip's use in a portable scope calibrator, a low-distortion oscillator, and as a logarithmic amplifier. □

Dual-function amplifier eases circuit design

by Jim Williams
National Semiconductor Corp., Santa Clara, Calif.

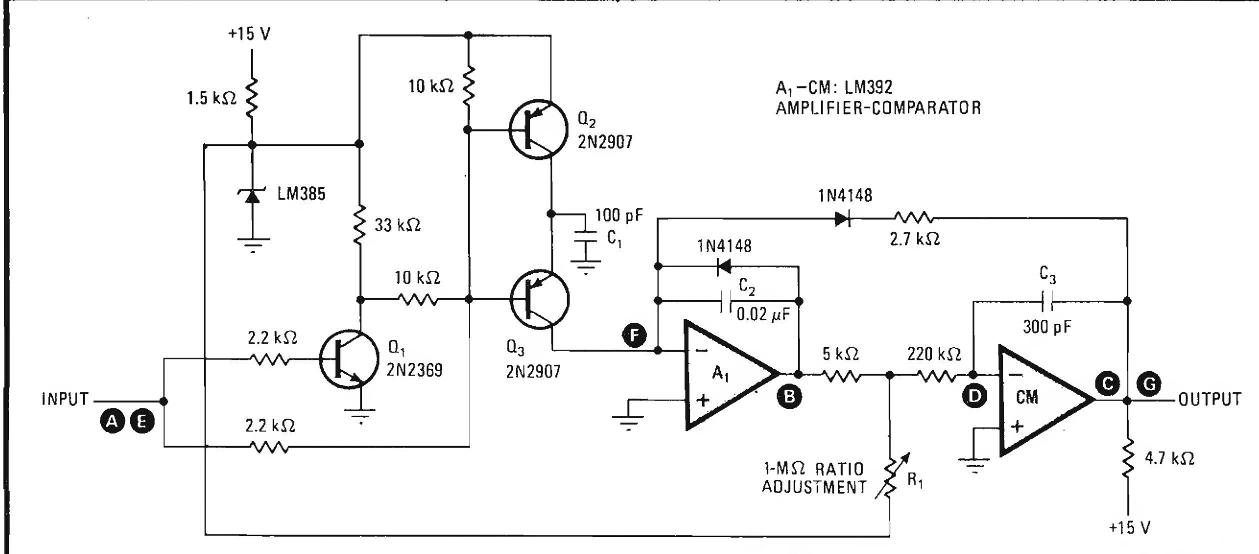
To simplify and cut the cost of the myriad of general-purpose and specialized circuits, chips like National's LM392 combine both amplifier and comparator functions on a single substrate. As has already been noted [*Electronics*, May 5, p. 142], it can be used to build a sample-and-hold circuit, a feed-forward low-pass filter and a linearized–platinum-resistor thermometer. This article will present designs for its use in the construction of a variable-ratio digital divider, an exponential voltage-to-frequency converter for electronic music, and a temperature controller for quartz-crystal stabilization.

Figure 1 shows a divider whose digital-pulse input can be divided by any number from 1 to 100 by means of a single-knob control. This function is ideal for bench-type work where the ability to set the division ratio rapidly is advantageous.

With no input signal, transistors Q_1 and Q_3 are off and Q_2 is on. Thus, the 100-picofarad capacitor (C_1) at the junction of Q_2 and Q_3 accumulates a charge equal to $Q_{cap} = C_1V_0$, where V_0 is the potential across the LM385 zener diode (1.2 volts), minus the saturated collector-to-emitter potential across Q_2.

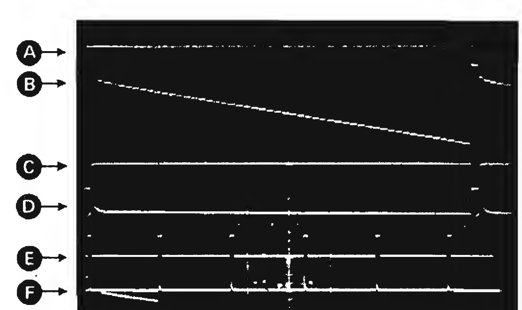
When the input signal to the circuit goes high (see trace A, in the photograph), Q_2 goes off and Q_1 turns on Q_3. As a result, the charge across C_1 is displaced into A_1's summing junction. A_1 responds by jumping to the value required to maintain its summing junction at zero (trace B).

This sequence is repeated for every input pulse. During this time, A_1's output will generate the staircase waveshape shown as the 0.02-microfarad feedback capacitor (C_2) is pumped by the charge-dispensing action to the A_1 summing junction. When A_1's output is

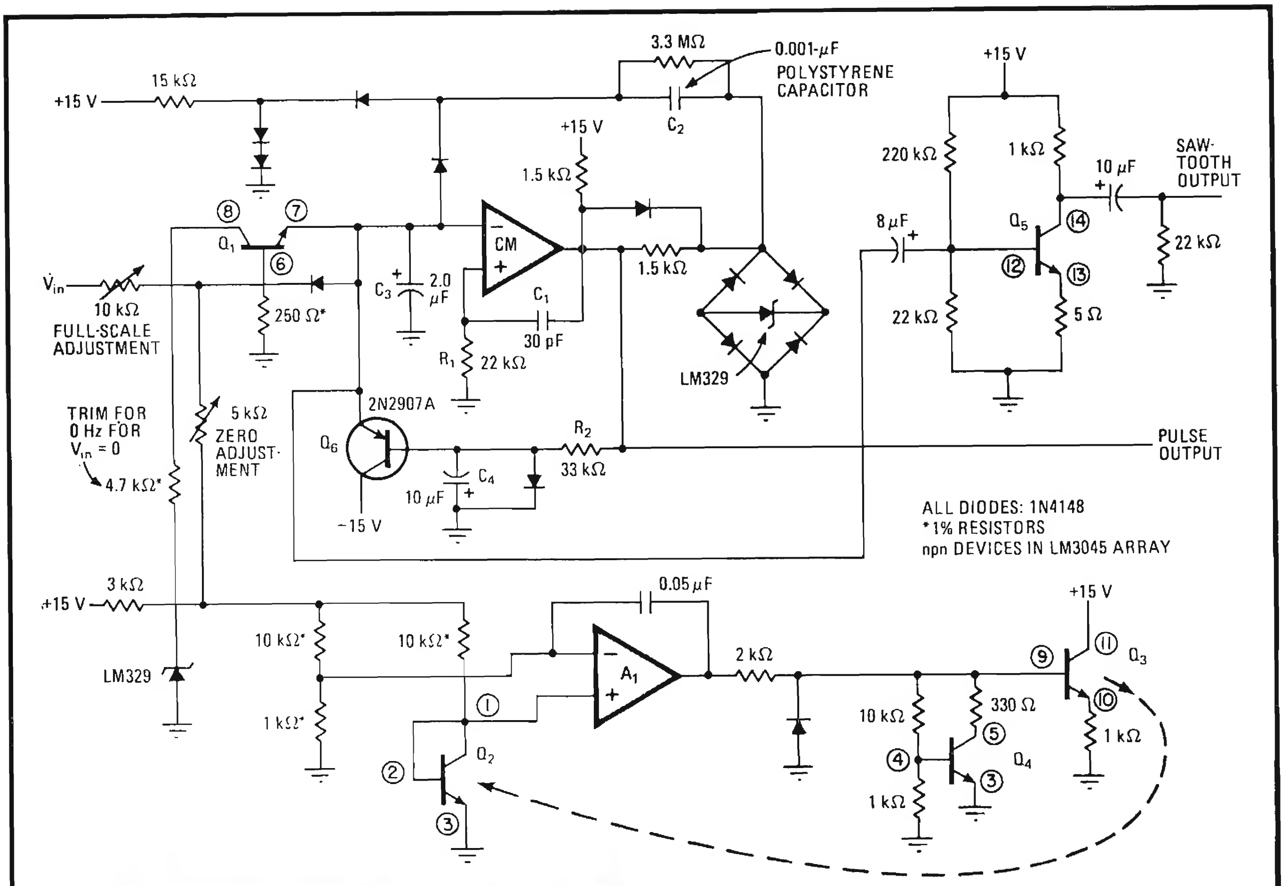


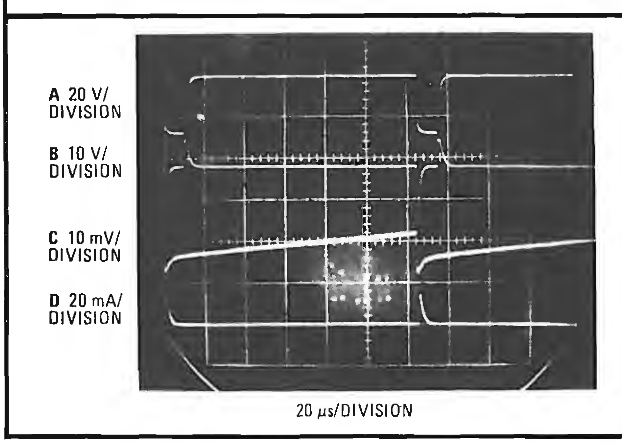
Trace	Vertical resolution (volts/division)*	Horizontal resolution (μs/division)
A	10	500
B	1	500
C	50	500
D	50	500
E	10	50
F	10 mA	50
G	0.1	50

*UNLESS OTHERWISE NOTED



1. Analog digitizer. A single-control potentiometer sets the digital signal's divider ratio from 1 to 100 using the LM392 comparator-amplifier chip. Thus, the division ratio may be rapidly set. Staircase signals are derived from a charge-balancing arrangement, which acts to maintain A_1's summing junction at a voltage null.





2. Sweet sawtooth. When combined with LM3045 transistor array, LM392 forms the heart of an exponential function generator that can easily be built. Waveform conformity to a pure exponential is excellent—±0.25% over the 20-Hz-to-15-kHz range. Thermal drift is minimized with a simple servo loop. Provision is made for eliminating servo lock-up under virtually all conditions.

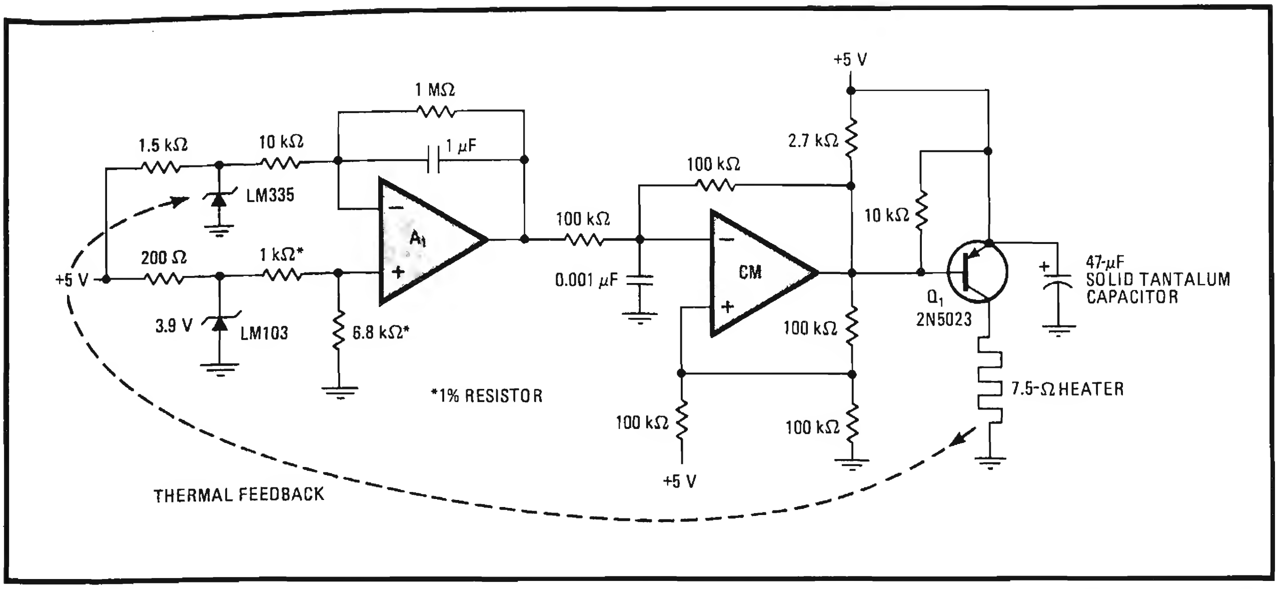
just great enough to bias the noninverting input of the comparator (CM) below ground, the output (trace C) goes low and resets A_1 to zero. Positive feedback to the comparator (trace D) is applied through the 300-pF capacitor (C_3), ensuring adequate reset time for A_1.

Potentiometer R_1 sets the number of steps in the ramp required to trip the comparator. Thus the circuit's input-to-output division ratio may be conveniently set. Traces E through G expand the scope trace to show the dividing action in detail. When the input E goes high, charge is deposited into A_1's summing junction F, and the resultant waveform G takes a step.

Professional-grade electronic-music synthesizers require voltage-controlled frequency generators whose output frequency is exponentially related to the input voltage. The one shown in Fig. 2 provides conformity within 0.25% over the range from 20 hertz to 15 kHz using a single LM392 and an LM3045 transistor array. These specifications will be adequate for all but the most demanding of applications.

The exponential function is generated by Q_1, whose collector current varies exponentially with its base-emitter voltage in accordance with the well-known relationship between that voltage and current in a bipolar transistor. An elaborate and expensive compensation scheme is usually required because the transistor's operating point varies widely with temperature. Here, Q_2 and Q_3, located in the array, serve as a heater-sensor pair for A_1, which controls the temperature of Q_2 by means of a simple servo loop. As a consequence, the LM3045 array maintains its constant temperature, eliminating thermal-drift problems in the operation of Q_1. Q_4 is a clamp, preventing the servo from locking up during circuit start-up.

In operation, Q_1's current output is fed into the summing junction of a charge-dispensing current-to-frequency converter. The comparator's output state is used to switch the 0.001-μF capacitor between a reference voltage and the comparator's inverting input, the reference



1. Oven cut. Quartz crystals are maintained at 75°C with this temperature controller, thus stabilizing output frequency of these sources. Switched-mode servo loop simplifies circuitry considerably. Long-term temperature accuracy is estimated at 10 parts per million.

being furnished by the LM329.

The comparator drives the capacitor C_1 and resistor R_1 combination, this network providing regenerative feedback to reinforce the direction of its output. Thus, positive feedback ceases when the voltage across the R_1C_1 combination decays, and any negative-going amplifier output will be followed by a single positive edge after the time constant R_1C_1 (see waveforms A and B in the photograph).

The integrating capacitor C_3 is never allowed to charge beyond 10 to 15 millivolts because it is constantly reset by charge dispensed from the switching of C_2 (trace C). If the amplifier's output goes negative, C_2 dumps a quantity of charge into C_3, forcing it to a lower potential (trace D). When a short pulse is transferred through to the comparator's noninverting input, C_2 is again able to charge and the cycle repeats. The rate at which this sequence occurs is directly related to the current into the comparator's summing junction from Q_1. Because this current is exponentially related to the circuit's input voltage, the overall current-to-frequency transfer function is exponentially related to the input voltage.

Any condition that allows C_3 to charge beyond 10 to 20 mV will cause circuit lock-up. Q_6 prevents this by pulling the inverting input of A_1 towards -15 V. The resistor and capacitor combination of R_2 and C_4 determines when the transistor comes on. When the circuit is running normally, Q_6 is biased off and is in effect out of the circuit.

The circuit is calibrated by simply grounding the input and adjusting first the zeroing potentiometer until oscillations just start and then the full-scale potentiometer so that the circuit's frequency output exactly doubles for each volt of input (1 V per octave for musical purposes). The comparator's output pulses while Q_5 amplifies the summing junction ramp for a sawtooth output.

The circuit in Fig. 3 will maintain the temperature of a quartz-crystal oven at 75°C. Five-volt single-supply operation permits the circuit to be powered directly from TTL-type rails.

A_1, operating at a gain of 100, determines the voltage difference between the temperature setpoint and the LM335 temperature sensor, which is located inside the oven. The temperature setpoint is established by the LM103 3.9-V reference and the 1-to-6.8-kilohm divider.

A_1's output biases the comparator, which functions as a pulse-width modulator and biases Q_1 to deliver switched-mode power to the heater. When power is applied, A_1's output goes high, causing the comparator's output to saturate low. Q_1 then comes on.

When the oven warms to the desired setpoint, A_1's output falls and the comparator begins to pulse-width–modulate the heater via the servo loop. In practice, the LM335 should be in good thermal contact with the heater to prevent oscillation in the servo loop. □

Bi-FET op amps invade 741's general-purpose domain

by Jim Williams
National Semiconductor Corp., Santa Clara, Calif.

Thanks to their low-drift microampere supply currents and picoampere bias currents, recently introduced bipolar field-effect-transistor operational amplifiers like National's LF441 can be used in applications that general-purpose amplifiers like the 741 cannot address. A high-performance pH meter, logarithmic amplifiers, and a voltmeter-checker reference source may be inexpensively built with this bi-FET operational amplifier.

The low-bias input of the 441 provides an excellent nonloading port for a pH probe, which is used to measure the acidity or alkalinity of a solution (Fig. 1). This simple four-chip interface yields a linear 0-to-10-volt output corresponding directly to the value of the pH (0 to 10) being measured, a range that is more than adequate for many applications.

The output from buffer A_1 is applied to A_2, a tuned 60-hertz filter that removes power-line noise. A_2 also biases op amp A_3, which provides a compensation adjustment for the probe's temperature. A_4 allows the probe to be calibrated.

To calibrate the circuit, the probe is immersed in a solution having a pH of 7. The solution's temperature is normalized for the meter by R_1, a 10-turn 1,000-ohm potentiometer whose value may be set between 0 and 100 units. These values correspond directly to a solution temperature range of 0° to 100°C. Potentiometer R_2 is then adjusted for an output voltage of 7 V.

A conventional logarithmic amplifier (Fig. 2a) utilizes the well-known logarithmic relationship between the base-to-emitter voltage drop in a transistor and its collector current. Here, A_1 acts as a clamp, forcing the current through Q_1 to equal the input current, E_{in}/R_{in}. Q_2 provides feedback to A_2, forcing Q_2's collector current to equal A_2's input current, which is established by the LM185 zener-diode reference.

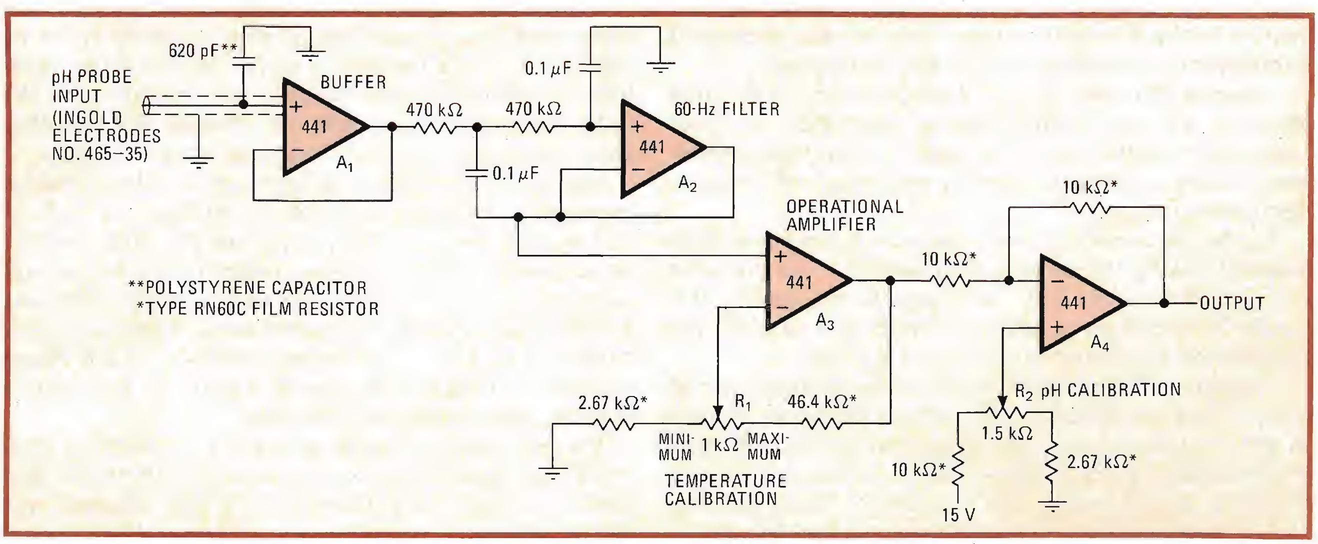
Because Q_2's collector current is constant, its emitter-to-base voltage is fixed. The base-to-emitter drop of Q_1, however, varies with the input current. The circuit's output voltage is therefore a function of the difference in the V_{be} voltages of Q_1 and Q_2 and is proportional to the logarithm of the input current. In this manner, the V_{be} drift is cancelled. The coefficient of this term will vary with temperature, however, and cause a drift in the output voltage. The 1,000-Ω thermistor compensates for this drift, stabilizing A_1's gain.

The 441's 50-pA bias current allows accurate logging down into the nanoampere region. With the values shown in the circuit, the scale factor for the amplifier is 1 V/decade.

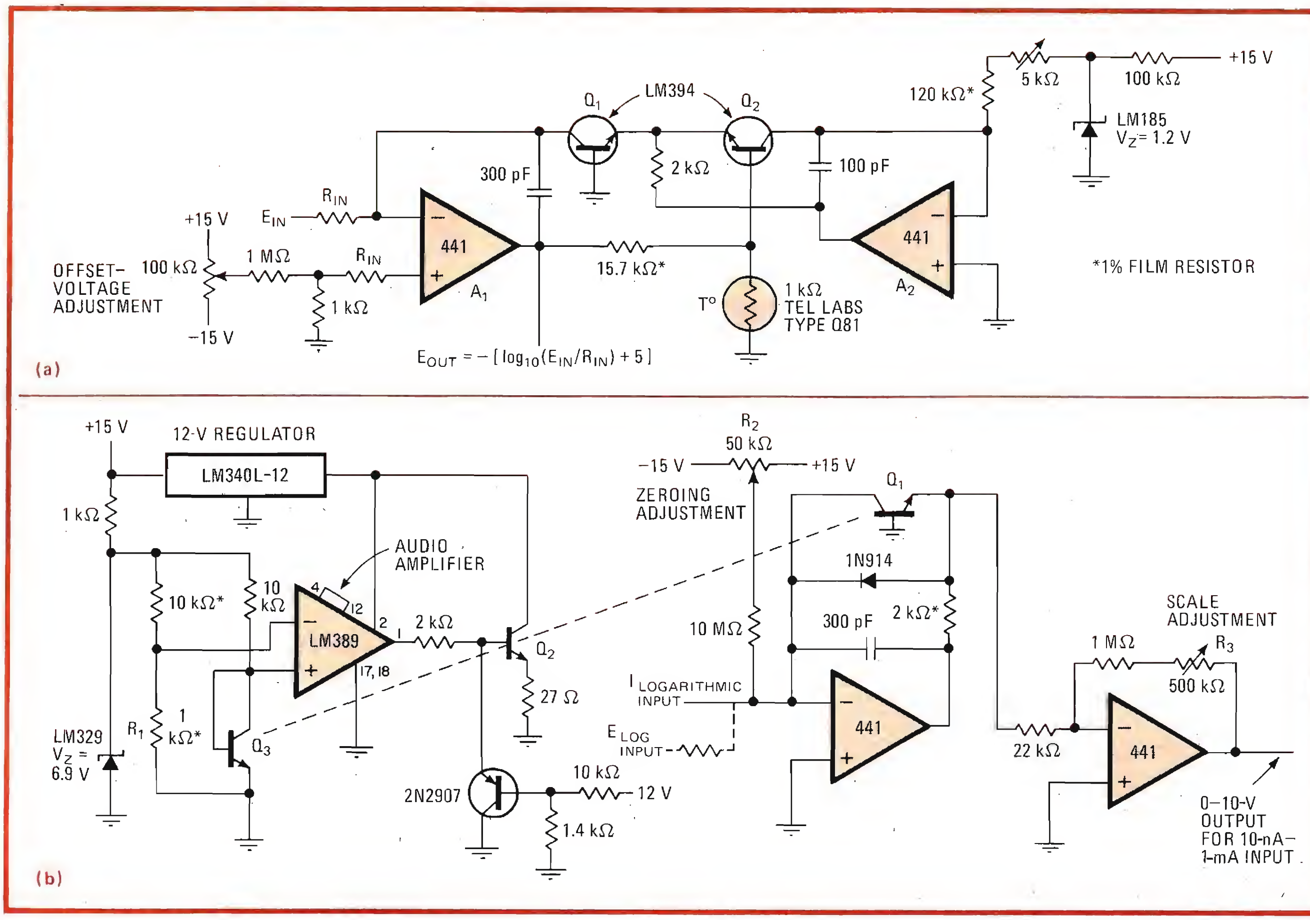
A second type of logarithmic amplifier is shown in (b). This unconventional design completely eliminates the temperature-compensation problems of (a) by temperature-stabilizing logging transistor Q_1. This temperature problem is economically eliminated by utilizing the LM389 audio-amplifier-and-transistor array as an oven to control the logging transistor's environment.

Transistor Q_2 in the LM389 serves as a heater, and Q_3 functions as the chip's temperature sensor. The LM389 senses Q_3's V_{be}, which is temperature-dependent, and drives Q_2 to feed back the chip's temperature to the set point established by the 1-to-10-kilohm divider. The LM329 reference ensures that the power supply is independent of temperature changes.

Q_1, the logging transistor, operates in this tightly controlled thermal environment. When the circuit is first

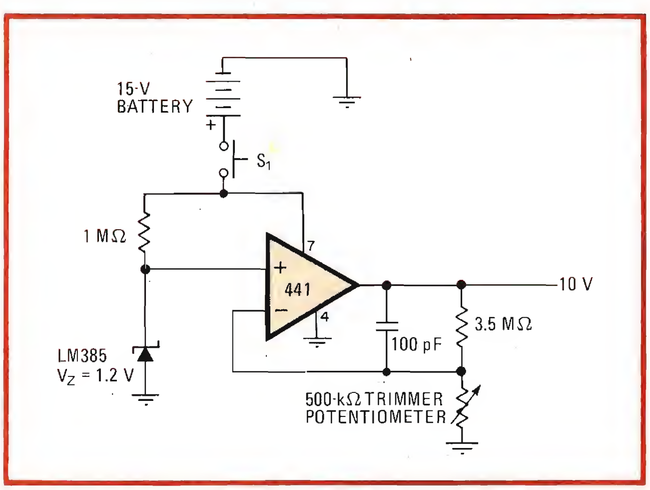


1. Acids and bases. This four-chip interface converts the output of a pH probe into direct readings of a solution's acidity and alkalinity. The circuit has a filter to reject the ac line noise that plagues instruments of this type. This unit can easily compensate for temperature variations.



2. Low-power loggers. With amplifier A_1 clamping current through transistor Q_1 to input value E_{in}/R_{in} and with A_2 holding Q_2's current constant with LM185's reference, circuit (a) yields a logarithmic response by virtue of proportional differences between Q_1 and Q_2's well-known V_{be}-to-collector current relation. A more advanced version (b) uses an LM389 to eliminate temperature effects on output.

turned on, Q_2's current flow becomes 50 milliamperes forcing the transistor to dissipate about 0.5 watt, which raises the chip to its operating temperature rapidly. At this point, the thermal-feedback circuit takes control and adjusts the chip's power dissipation accordingly. The LM340L voltage regulator has only 3 V across it, so it



3. Long-term accuracy. Using a single LF441 and a 1.2-volt reference, this circuit for calibrating digital voltmeters with a 10-V signal draws only 250 microamperes. Using a 15-V power source, the circuit has an output accuracy within 0.1% over a year's time.

never dissipates more than about 0.3 W. The pnp-transistor clamp at the base of Q_2 prevents feedback lock-up during circuit start-up.

To adjust this circuit, the base of Q_2 should be grounded, then the power applied to the circuit, and the collector voltage of Q_3 measured at room temperature. Next, Q_3's potential at 50°C is calculated, a drop of -2.2 millivolts/°C being assumed. The value of R_1 should be selected to yield a voltage close to the calculated potential at the LM389's negative input. After Q_2's base is removed from ground, the circuit will be operational.

A_1's low bias current allows values as low as 10 nanoamperes to be logged within 3%. Potentiometer R_2 provides zeroing for the amplifier. Potentiometer R_3 sets the overall gain of the circuit.

The low power consumption of the 441 is useful in a calibration checker for digital voltmeters that only draws 250 μA (Fig. 3). Here, the 441 is used as a noninverting amplifier. The LM385 is a low-power reference that provides 1.2 V to the input. This voltage is simply scaled by the feedback-resistor network to yield exactly 10 V at the circuit's output. The circuit will be accurate to within 0.1% for over a year, even with frequent use. □

Bi-FETs expand applications for general-purpose op amps

by Jim Williams
National Semiconductor Corp., Santa Clara, Calif.

With their excellent low-power consumption and low drift, bipolar field-effect-transistor operational amplifiers easily outperform general-purpose (741-type) op amps in a variety of applications [*Electronics*, Nov. 3, 1981, p. 134]. A low-power voltage-to-frequency converter, a battery-powered strip-chart preamplifier, and a high-efficiency crystal-oven controller can also benefit from those qualities of the 441 op amp.

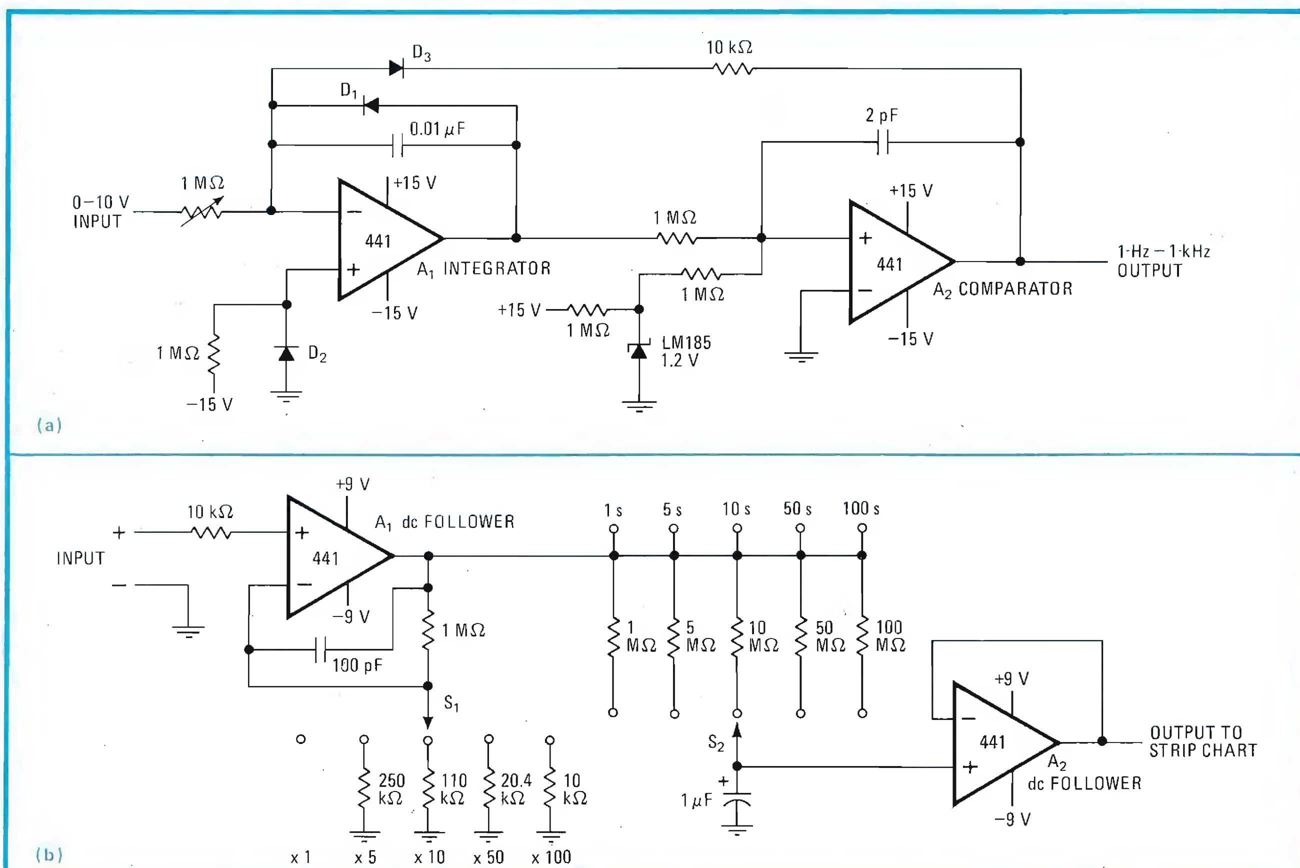
The voltage-to-frequency converter (Fig. 1a) provides linearity to within 1% over the range of 1 hertz to 1 kilohertz. What is more, it does not need an integrator-resetting network using an FET switch, and its current drain is only 1 milliampere.

Integrator A_1 generates a ramp whose slope is proportional to the current into the amplifier's summing junction. The ramp's amplitude is then compared with the 1.2-volt reference at A_2, which serves as a current-summing comparator.

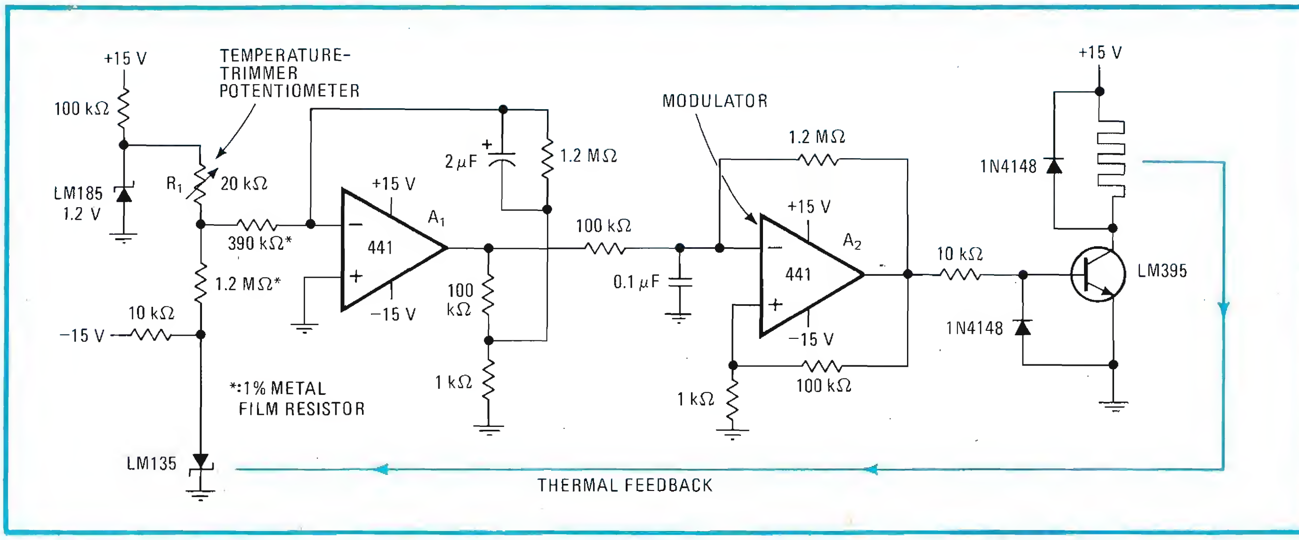
When the instantaneous amplitude of the ramp exceeds -1.2 V, A_2's output goes low, thereby pulling current from A_1's summing junction. This pulling, aided by diode D_1, causes A_1's output to drop quickly to zero. D_2 biases A_1's noninverting input, providing temperature compensation for the amplifier. These diodes and D_3 are 1N4148 parts.

The 2-picofarad capacitor at A_2 ensures that the output of the amplifier will remain high long enough to completely discharge the 0.01-microfarad capacitor at A_1, thus doing the job of the integrator-reset mechanism. As for calibration, the output is easily adjusted with the 1-megohm potentiometer for a 1-kHz output that is given an input voltage of 10 V.

The 441's low-bias current and its low-power consumption can also yield a simple and flexible preamplifier for strip-chart recorders (Fig. 1b). The circuit is powered by two standard 9-V batteries and may be plugged directly into the recorder's input. As a result, common-mode and ground-loop difficulties are minimized. The gain is variable from 1 to 100, and the time



1. Low current, low cost. A voltage-to-frequency converter and preamplifier for strip-chart recorders may be built with the 441 bi-FET op amp. Converter (a), which is easily reset by a capacitor at A_2, provides linearity within 1% over a 0-to-1-kilohertz range and draws only 1 milliampere. A battery-powered preamplifier (b) has an adjustable gain and time constant. The circuit draws less than 500 microamperes.



2. Heat switch. This feedback-type controller, using a switching modulator to conserve power, maintains the crystal temperature at about 75°C. Temperature, which may be trimmed over a 4° C range with potentiometer R_1, can be held to within ±0.1°C for a long time.

constant is adjustable from 1 to 100 seconds.

Input amplifier A_1 operates as a dc follower with gain. The gain has five ranges and is selected by S_1. The operational amplifier's input impedance is extremely high (10^{12} ohms) and consequently bias-current loading at the input is around 50 picoamperes. The 10-kilohm resistor in the input line provides current limiting under fault (overloaded input) conditions.

A_2, a second dc follower, buffers the RC filter composed of five resistors and a capacitor. The time constant is selected by switch S_2. This circuit draws less than 500 microamperes, ensuring long battery life.

The efficiency of the crystal-oven controller circuit (Fig. 2) is improved by having power switched across the heater element, instead of using a conventional linear-control arrangement. Oven temperature is sensed by the LM135 temperature sensor, whose output varies 10 millivolts/°C; thus its output will be 2.98 v at 25°C. This signal, converted into current as it flows through the 1.2-MΩ resistor, is then summed with a current derived from the LM185 voltage reference.

A_1 amplifies the difference between these two currents and drives A_2, a free-running duty-cycle modulator, over several kilohertz of frequency to power the output transistor and the heater.

Generally, when power is applied to the circuit, A_1 attains a negative saturation, forcing A_2's output to a positive one. The LM395 then turns on and the oven warms. When the oven is within 1°C of the desired setting, A_2 becomes unsaturated and runs at a duty cycle dependent upon A_1's output voltage. The duty cycle is determined by the temperature difference between the oven and the setpoint. For the given values, the circuit will maintain an oven temperature at 75°C, ±0.1°C. □